Augmentation Techniques for Efficient Exploration in Head-Mounted Display Environments

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Abstract

Physical characteristics and constraints of today's head-mounted displays (HMDs) often impair interaction in immersive virtual environments (VEs). For instance, due to the limited field of view (FOV) subtended by the display units in front of the user's eyes more effort is required to explore a VE by head rotations than for exploration in the real world.

In this paper we propose a combination of two augmentation techniques that have the potential to make exploration of VEs more efficient: (1) augmenting the geometric FOV (GFOV) used for rendering the VE, and (2) amplifying head rotations while the user changes her head orientation. In order to identify how much manipulation can be applied without users noticing, we conducted two psychophysical experiments in which we analyzed subjects' ability to discriminate between virtual and real head pitch and roll rotations while three different geometric FOVs were used. Our results show that the combination of both techniques has great potential to support efficient exploration of VEs. We found that virtual pitch and roll rotations can be amplified by 30% and 44% respectively, when the GFOV matches the subject's estimation of the most natural FOV. This leads to a possible reduction of the user's effort required to explore the VE using a combination of both techniques by approximately 25%.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

Keywords: Head-mounted displays, head motion perception, geometric field of view

1 Introduction

In the real world, long-term evolutionary natural selection optimized the complex interplay of human actions and multi-sensory feedback evaluation. In particular, the ability to explore our surroundings by means of our eyes and coordinated head motions is very sophisticated. Unfortunately, until now this important ability has not been transferred appropriately to immersive virtual reality (VR) environments. Immersive head-mounted displays (HMDs) are one of the most popular virtual display devices which have the potential to support a natural viewing experience in a virtual world. However, physical characteristics of today's HMDs such as size, weight, wires, and field of view (FOV) hamper efficient exploration of virtual environments (VEs). For instance, the limited FOV allows users to see only a portion of the VE, while most parts that would be visible to humans in the real world due to peripheral vision are blocked. When standing upright in the real world, it is easy for a human to look at her feet by simply pitching her head and eyes downwards by an angle of approximately $45°$. Attempting the same task while wearing a HMD requires the user to bend forward, resulting in more effort as illustrated in Figure 1.

Moreover, in HMD environments users have to apply greater muscle force to the neck in order to adjust their head posture to compensate for the HMD characteristics. Consequently, head movements with HMDs often appear cumbersome and constrained, and often it is more strenuous for users to perform specific tasks or even worse, musculoskeletal problems may arise from prolonged posture adoption [Baber et al. 1999]. These arguments underscore the importance and need for methods to improve comfort of HMDs and to reduce neck fatigue or even to prevent injury. Although some wide field of view HMDs are available, unfortunately, the tradeoff between the HMD's FOV and the resolution, cost, and weight, makes HMDs with a FOV comparable to human vision unlikely in the foreseeable future [Melzer et al. 2009]. Hence, solutions are highly desirable that do not rely on hardware changes, but reduce the user's effort required to explore the VE.

In order to satisfy this requirement, we propose the combination of two augmentation techniques:

- augmenting the geometric FOV (GFOV) used for rendering the VE, and
- amplifying head rotations while the user changes her head orientation.

Considering the first aspect, researchers have proposed to compress visual information in the limited FOV of a HMD by increasing the GFOV that is applied in the rendering process [Kuhl et al. 2009]. But for an undistorted view to the virtual world in a HMD environment the perspective projection in the rendering process has to be adjusted to the FOV of the HMD. Increasing the GFOV augments the virtual aperture angle that is used for rendering the VE and thus reduces the need for head motions in visual search tasks. However, this manipulation distorts the perception of geometry of virtual objects [Steinicke et al. 2009] and spatial relations in the VE [Kuhl et al. 2009], since the virtual scene appears minified. Until now, hardly any research has focused on analyzing the effects of manipulating the GFOV, and in particular the impact of such perspective distortions on motion perception has not yet been evaluated.

Tracked head rotations, in particular yaw and pitch rotations, enable natural exploration of VEs. However, due to the limited FOV of HMDs, more frequent and larger head motions are required, for example, in visual search tasks [Alfano and Michel 1996; Jay and Hubbold 2003]. Roll rotations are used primarily in specific tasks,

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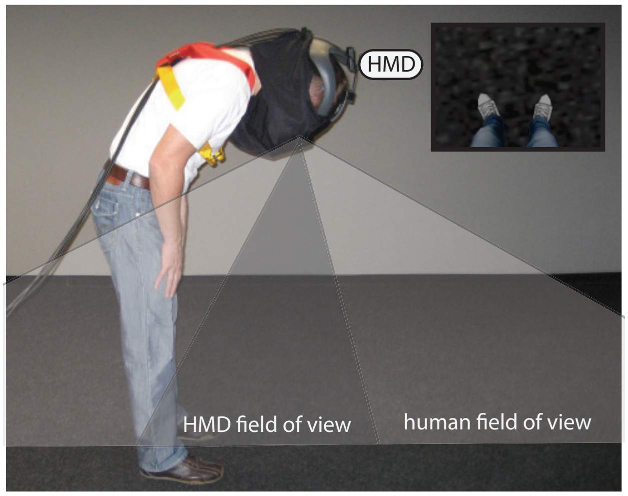


Figure 1: *User in a HMD environment trying to look at his virtual body (virtual view is illustrated as inset). The frustums show the real vs. the virtual field of view.*

e. g., viewing vertical planes, but are often used in combination with yaw and pitch rotations. It appears reasonable to amplify a user's head rotation in such a way that, for instance, a tracked pitch rotation is mapped to a larger virtual camera pitch instead of using a one-to-one mapping. While rotating the head in the real world, sensory information such as vestibular, proprioceptive, and efferent copy signals as well as visual information create consistent multi-sensory cues that indicate one's own motion. Conversely, due to tracking errors and latency in HMD environments, often visual cues presented on the HMD as well as vestibular and proprioceptive cues from motions in the real world do not match. Investigating the effect of latency on perceptual stability of the VE, researchers found that subjects were not able to detect small inconsistencies between real and virtual yaw rotations [Jerald et al. 2008; Jaekl et al. 2002]. Results motivated that users may judge the virtual world as stable when the virtual rotation is slightly amplified in comparison to the real yaw rotation [Jerald et al. 2008]. Furthermore, users tend to unwittingly compensate for small inconsistencies between vision and vestibular sensation [Steinicke et al. 2009].

In this paper we address the challenge of combining the approaches of augmenting the GFOV and amplifying head rotations. Until now, most research has focused on manipulating yaw rotations, but fewer experiments have considered roll and pitch rotations. Therefore, we present two experiments in which we have quantified by how much humans' head pitch and roll rotations can be manipulated for different geometric FOVs without users observing inconsistencies between real and virtual rotations. The remainder of this paper is structured as follows. Section 2 summarizes related work. Section 3 describes the two augmentation techniques. Section 4 presents the psychophysical experiments and reports the results, which are discussed in Section 5. Section 6 concludes the paper and gives an overview of future work.

2 Related Work

Due to their ability to immerse users in VEs and provide a high level of presence, HMDs are one of the most popular virtual display devices [Hendrix and Barfield 2000]. The head-tracking facility enables an intuitive and natural navigational interface [Waller 1999]. However, as mentioned above HMDs introduce some downsides, in particular, a limited field of view, which forces the user to perform larger and more frequent head motions. In addition, the ergonomics of the HMD such as weight and wear discomfort further downgrade their usability. Previous research in the domain of biodynamics has revealed that head-supported loads of 350g to 1450g significantly increase the flexion of neck and trunk postures (cf. Figure 1). Posture adoption requires a greater muscle force (i. e., a greater musculoskeletal stress) that may lead to detriments ranging from fatigue and inducement of pain to the development of musculoskeletal disorders around the shoulder and neck region [Baber et al. 1999; Melzer et al. 2009; Knight and Baber 2007].

Field of View

The FOV of a HMD refers to the horizontal and vertical angles subtended by the display units in front of the user's eyes. Usually a larger FOV results in an increased sense of presence and better situational awareness [Lin et al. 2002]. However, most HMDs do not cover the entire visual field of the human eyes and support only a considerably smaller FOV [Marieb 1992; Melzer et al. 2009; Keller and Colucci 1998]. Commercially available HMDs typically have fields of view which range from 20 to 120 degrees diagonally, whereas the effective visual field of humans is approximately 200 degrees horizontally and 150 degrees vertically [Warren and Wertheim 1990]. Previous research suggests that FOVs smaller than approximately 40° diagonal may downgrade target acquisition, self-motion perception and sense of presence [Melzer et al. 2009; Keller and Colucci 1998].

In order for a virtual world to be displayed on a HMD, the computer graphics system must determine which part of the VE is to be viewed by the user. If the GFOV matches the field of view of the HMD, the viewport is mapped from virtual space onto the physical display in such a way that users perceive a "correct" perspective (assuming that we neglect other distortions of the display device such as pincushion distortion). In order to provide users a wider view to the VE, it sounds reasonable to apply a larger geometric field of view, for instance a GFOV that matches the visual aperture angle of the human eye. However, if the GFOV varies from the display's FOV, it results either in *mini-* or *magnification* of the graphics [Kuhl et al. 2009]. If the GFOV is smaller than the FOV of the HMD, the viewport image will appear magnified on the physical display because of the requirement for the image to fill a larger subtended angle in real space versus virtual space. Conversely, if the GFOV is larger than the FOV of the HMD, a larger portion of the VE needs to be displayed in the viewport, which will appear minified. Until now, it is not well understood how optical distortions and mini- as well as magnification impact a user's scene perception. However, [Steinicke et al. 2009] have shown that an increased GFOV appears more natural to users, and [Kuhl et al. 2009] showed that minification may account for some of the often observed underestimation in distance judgments in HMD environments [Interrante et al. 2006].

Scene Motion Perception

During translational and rotational head motions in the real world healthy humans perceive the environment to be stable and stationary [Bridgeman et al. 1994; Wallach 1987; Wertheim 1994]. The human perceptual system derives information about self motion from a variety of sensory sources, including visual motion cues as well as extraretinal cues, such as linear and angular head accelerations provided by the vestibular system, proprioceptive information about the postural body state, and our cognitive model of the world. Ambiguities or conflicts between different motion cues appear in the real world to a much lower extent than in immersive VEs; however, different studies have shown that users tolerate certain amounts of inconsistencies in immersive VEs [Burns et al. 2005; Jerald et al. 2008; Peck et al. 2008; Jaekl et al. 2002]. Until recently, hardly any research has been undertaken in order to identify thresholds which indicate the tolerable amount of deviation between vision and proprioception while the user is turning her head. Some work has been done in order to identify thresholds for detecting scene motion during yaw rotation [Jerald et al. 2008; Wallach 1987], but roll and pitch angles were not considered in these experiments. Interestingly, these works found that subjects perceive a stable image during yaw rotation mainly when the virtual rotation is amplified relative to the physical rotation. [Jaekl et al. 2002] found similar results for stable pitch and roll rotations, but the interrelation of different GFOV and head rotation gains was not tested, and both the visual stimulus and the method to determine stability thresholds differs from our approach (cf. Section 4).

3 Augmentation Techniques

Hardware-based field of view restrictions of HMDs can be partially compensated in software by augmenting the geometric field of view and/or amplifying head rotations. Both approaches allow users to explore a virtual scene with an effort similar to using a HMD with a larger FOV (discussed in detail in Section 5).

3.1 Geometric Field of View Gains

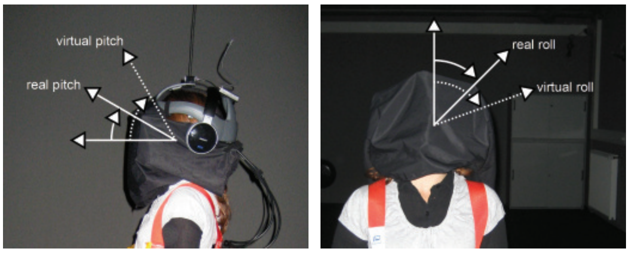
If the GFOV matches the field of view of the HMD, the viewport is mapped from virtual space onto the physical display in such a way that users perceive a "correct" perspective. However, as mentioned in Section 1, experiments have revealed that subjects judge a virtual scene as most natural, which is rendered with a diagonal GFOV that is 14.9% larger than the display's diagonal field of view (DFOV) [Steinicke et al. 2009].

In order to manipulate the GFOV we apply *field of view gains* $g_{F[x]} \in \mathbb{R}_+$ and $g_{F[y]} \in \mathbb{R}_+$ to the virtual camera frustum by replacing the horizontal angle *fovx* and the vertical angle *fovy* of the GFOV by $g_{F[x]} \cdot fovx$ and $g_{F[y]} \cdot fovy$, respectively.[1] In the following we will focus on the vertical GFOV gains $g_{F[y]}$, since the horizontal gain can be calculated with respect to the aspect ratio of the HMD. If GFOV matches the DFOV, i. e., $GFOV = DFOV$, the virtual scene is displayed without distortion. In the case $g_{F[y]} > 1$ the GFOV is increased and the virtual scene appears minified (cf. Section 2), whereas with a gain $g_{F[y]} < 1$ the GFOV is decreased and therefore the virtual scene appears magnified. Assuming that we consider a HMD with a DFOV of $80°$, when applying a field of view gain $g_{F[y]} = 1$, the scene is rendered with a matching GFOV of $80°$. The field of view gain $g_{F[y]} = 0.5$ means that the GFOV used to render the scene is decreased by 50% to $40°$, whereas $g_{F[y]} = 1.5$ scales the GFOV by 50% to $120°$.

3.2 Head Rotation Gains

Manipulation of head rotations results in the virtual scene either appearing to move slightly with or against the head rotation direction. If the difference between real and virtual head motion is too large, the virtual scene might appear unstable and/or the user will not be able to correctly judge her motions (cf. Section 2). In an IVE, manipulation of head rotations can be implemented using *rotation gains*. These gains are applied to a rotation triple that describes the head orientation in the real world. Similar as FOV gains, head rotation gains take advantage of the imperfections of the human visual-vestibular system by intentionally injecting imperceptible manipulations to the scene. Tracked real-world rotations can be specified by a vector consisting of three angles, i. e., $R_{real} := (pitch_{real}, yaw_{real}, roll_{real})$. Rotation gains are defined for each component (i. e., pitch, yaw, and roll) of the rotation

[1] If not stated otherwise, GFOV refers to the *diagonal* geometric FOV.



(a) Manipulation of pitch rotations. (b) Manipulation of roll rotations.

Figure 2: *Rotation gains applied to (a) pitch and (b) roll head rotations resulting in either amplified or attenuated virtual rotations.*

and are applied to the corresponding axis of the camera coordinates. A rotation gain tuple $g_R \in \mathbb{R}^3_+$ is defined as the quotient of the components of a virtual and real-world rotation, i. e.,

$$g_R := \left(\frac{pitch_{virtual}}{pitch_{real}}, \frac{yaw_{virtual}}{yaw_{real}}, \frac{roll_{virtual}}{roll_{real}}\right).$$

If a pitch rotation gain $g_{R[pitch]} = \frac{pitch_{virtual}}{pitch_{real}}$ is applied to a real world pitch rotation $pitch_{real}$, the virtual camera is rotated by $pitch_{real} \cdot g_{R[pitch]}$ instead of $pitch_{real}$. Figure 2 illustrates the difference between virtual and real pitch and roll rotations when a rotation gain is applied. If $g_{R[pitch]} = 1$ the virtual scene remains stable with respect to the head's orientation change. In the case $g_{R[pitch]} > 1$ the virtual scene appears to move against the direction of the head turn, i. e., real head-movements are amplified before they are mapped to the virtual camera. Conversely, a gain $g_{R[pitch]} < 1$ causes the scene to rotate in the direction of the head turn, i. e., real head-movements are attenuated before they are mapped to the virtual camera. For instance, if the user rotates her head by a pitch angle of $45°$, a gain $g_{R[pitch]} = 1$ maps this motion one-to-one to a $45°$ rotation of the virtual camera in the VE. Applying a gain $g_{R[pitch]} = 0.5$ results in the user having to rotate her head by $90°$ physically in order to achieve a $45°$ virtual rotation, and applying a gain $g_{R[pitch]} = 2$ results in the user having to rotate her head by only $22.5°$ physically in order to achieve a $45°$ virtual rotation. The same applies for roll and yaw rotation gains.

4 Experiments

In this section we present experiments in which we have quantified by how much pitch and roll head rotations can be manipulated in HMD environments without users noticing. In the experiments we analyzed subjects' sensitivity to rotation gains $g_{R[pitch]}$ and $g_{R[roll]}$ applied during head motions (cf. Section 3), and the impact of different field of view gains $g_{F[y]}$.

4.1 Experimental Design

For visual stimulus presentation in the experiments we used a virtual replica of our laboratory, which was modeled as a set of texture-mapped polygons and aligned to our real laboratory with millimeter accuracy. The texture maps were generated from photographs taken from the laboratory room as well as objects located in the laboratory, such as tracking cameras and computer equipment.

Hardware Setup

We performed all experiments in a $10m \times 7m$ darkened laboratory room. The subjects were equipped with a HMD (Rockwell Collins ProView SR80, 1280×1024@60Hz) for the visual stimulus presentation. We determined the exact diagonal FOV of $76.88°$ for this display as described in [Steinicke et al. 2009], which varies from the specification of the HMD's manufacturer, i. e., $80°$. On top of the HMD an InertiaCube 3 (InterSense) with an update rate of 180Hz was fixed for three degrees of freedom head orientation tracking. The entire head supported weight approximated 0.83kg. In the experiments we used an Intel computer with dual-core processors, 4GB of main memory and an *n*Vidia GeForce 8800 GTX for visual display, system control and logging purposes.

The virtual scene was rendered stereoscopically using the IrrLicht rendering engine and our own software with which the system maintained a frame rate of 60 frames per second. During the experiment the room was darkened, and a black curtain was fixed around the HMD in order to reduce the subjects' perception of the real world. The subjects received instructions on slides presented on the HMD. A Nintendo Wii remote controller served as input device via which the subjects judged perceived discrepancies between real and virtual head rotations. Beside a supervised training phase of 10 trials at the beginning of the experiments, no communication between experimenter and subjects was performed during the experiments in order to focus subjects on the tasks.

Participants

18 male and 5 female (age 22-37, ø: 25.52) subjects participated in the study. Subjects were students or members of the departments (computer science, mathematics, psychology and physics). All had normal or corrected to normal vision; 6 wore glasses and 3 contact lenses during the experiments. 5 had no experience with 3D games, 6 had some, and 12 had much experience. All subjects were naïve to the experimental conditions. 4 of the subjects had much experience with HMD setups, 3 had some, and 16 had no experience. 5 subjects had participated in experiments involving HMDs before. Some subjects obtained class credit for their participation. The total time per subject including pre-questionnaire, instructions, familiarization with the laboratory, training, experiments, breaks, and debriefing took 2 hours. Subjects were allowed to take breaks at any time; breaks between the experimental conditions were mandatory.

Methods

For all experiments we used the method of constant stimuli in a *two-alternative forced-choice* (2AFC) task [Ferwerda 2008]. In the method of constant stimuli, the applied head rotation gains $g_{R[pitch]}$ and $g_{R[roll]}$ are not related from one trial to the next, but presented randomly and uniformly distributed. The subject chooses between one of two possible responses, i. e., "Was the virtual rotation *larger* or *smaller* than the physical rotation?"; responses like "I can't tell." were not allowed. Hence, if subjects cannot detect the signal, they are forced to guess, and will be correct on average in 50% of the trials. The gain at which the subject responds "smaller" in half of the trials is taken as the *point of subjective equality* (PSE), at which the subject perceives the physical and the virtual rotation as identical. As the gain decreases or increases from this value the ability of the subject to detect the difference between physical and virtual rotation increases, resulting in a psychometric curve for the discrimination performance. Sensory thresholds are the points of intensity at which subjects can just detect a discrepancy between physical and virtual rotation. However, stimuli at values close to the thresholds often will not be detected. Therefore, we consider thresholds to be the gains at which the manipulation is detected only some proportion of the time. In psychophysical experiments, the point at which the curve reaches the middle between the chance level and 100% correct detections is usually taken as threshold. Therefore, we define the *detection threshold* (DT) for gains smaller than the PSE to be the gain at which the subject has 75% probability of choosing the "smaller" response correctly and the detection threshold for gains greater than the PSE to be the gain at which the subject chooses the "smaller" response in only 25% of the trials (since the correct response "larger" was then chosen in 75% of the trails). The 25% to 75% range of gains will give us an interval of possible manipulations, which can be used to manipulate pitch and roll head rotations.

As mentioned above, the limited FOVs of HMDs hinder an efficient exploration of a VE. Amplifying head rotations and/or augmenting the GFOV may compensate this drawback, but potentially influence scene and motion perception. In order to analyze the mutual impact of these approaches, we considered the interrelation of different fields of view and head rotation gains. In the experiments we analyzed the subjects' sensitivity to different head rotation gains $g_{R[pitch]}$ and $g_{R[roll]}$ under the following conditions:

- **Condition D** (GFOV=$76.88°$): the HMD's native DFOV,
- **Condition N** (GFOV=$88.34°$): the GFOV that subjects judged as most natural for the HMD [Steinicke et al. 2009],
- **Condition L** (GFOV=$98.62°$): a significantly larger GFOV.

With condition D we focus on the standard situation in which the GFOV matches the DFOV. With condition N we examine the influence of a GFOV that provides a more "natural" viewing experience [Steinicke et al. 2009]; this GFOV is increased by 14.9% relative to the GFOV as used for condition D. With the last condition L, we consider the impact of a significantly larger GFOV. Therefore, in our experiment we used the default field of view of our rendering system (i. e., Irrlicht Engine), which corresponds to a GFOV that is increased by 28.3% relative to the GFOV as used for condition D. The different GFOVs can be obtained simply by applying the field of view gains $g_{F[y]} \in \{1.0,\ 1.1848,\ 1.3649\}$ (cf. Section 3).

Subjects filled out Kennedy's simulator sickness questionnaire (SSQ) immediately before and after the experiments as well as the Slater-Usoh-Steed (SUS) presence questionnaire.

4.2 Experiment 1 (E1): Discrimination between Virtual and Physical Pitch Rotations

In this experiment we analyzed subjects' ability to discriminate whether a simulated virtual pitch rotation was larger or smaller than the corresponding physical head rotation. Therefore, we instructed the subjects to perform head pitch rotations with the HMD (see Figure 2(a)). We mapped this head rotation to a corresponding virtual camera rotation to which different rotation gains $g_{R[pitch]}$ were applied under three different field of view gain $g_{F[y]}$ conditions (see Section 3).

4.2.1 Material and Methods for E1

At the beginning of each trial an adjustment screen was presented on the HMD together with the written instruction to physically adjust the head orientation to the start values, which were given at physical head pitch and roll angles of $0°$ with a tolerance of $\pm 2°$. After assuming the initial head orientation, we displayed the task as inset to the subject to either pitch their head upwards or downwards. Subjects had to confirm the task by a button press on the Wii controller, before the virtual scene was presented on the HMD. When the subject had performed a physical pitch rotation of $40°$ the virtual scene was replaced by the written instruction to judge the discrepancy between real and virtual rotation in a 2AFC task. The subject had to decide whether the virtual rotation was larger (up button) or smaller (down button) than the real rotation, before the next trial started.

In randomized order we simulated different gains ranging between $g_{R[pitch]} = 0.6$ ($24°$ virtual rotation) and $g_{R[pitch]} = 1.4$ ($56°$

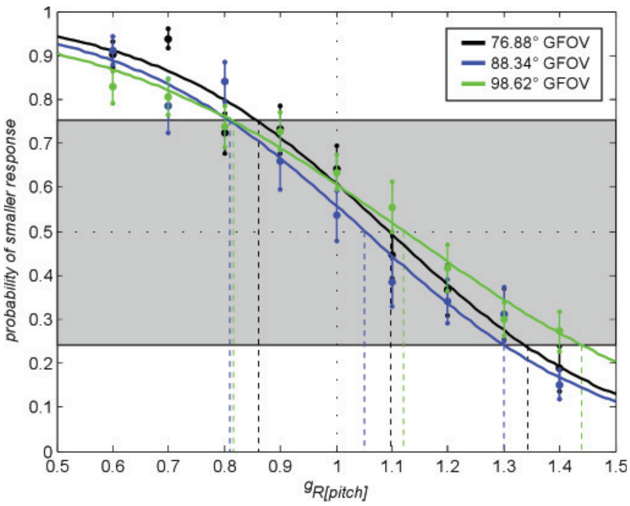


Figure 3: *Pooled results of the discrimination between virtual and physical pitch rotation under (black) condition D ($g_{F[y]} = 1.0$), (blue) condition N ($g_{F[y]} = 1.1848$), and (green) condition L ($g_{F[y]} = 1.3649$). The x-axis shows the applied rotation gain $g_{R[pitch]}$, the y-axis shows the probability of estimating a virtual rotation as "smaller" than the physical counterpart.*

virtual rotation) in steps of 0.1. Each gain was tested 8 times in randomized order leading to 72 trials. Furthermore, we tested these gains for the three conditions D, N, and L (cf. Section 4.1) in randomized order, resulting in 216 trials in total. We randomly chose the rotation direction between up and down for each trial. Before the experiment trials, subjects performed 10 supervised training trials with alternating gains $g_{R[pitch]} = 0.5$ (20° virtual rotation) and $g_{R[pitch]} = 1.8$ (72° virtual rotation) not included in the experiment results to ensure that all subjects correctly understood the task.

4.2.2 Results of E1

Figure 3 shows the mean response over all subjects of the discrimination experiment for the three conditions. The black function shows the results for condition D ($g_{F[y]} = 1.0$), the blue function for condition N ($g_{F[y]} = 1.1848$), and the green function for condition L ($g_{F[y]} = 1.3649$). The x-axis shows the applied rotation gain $g_{R[pitch]}$, the y-axis shows the probability that subjects estimated the virtual rotation as "smaller" than the physical rotation. The solid lines show the fitted psychometric functions of the form $f(x) = \frac{1}{1+e^{a \cdot x+b}}$, with $a, b \in \mathbb{R}$. Since we found no significant difference between upward or downward pitch rotations, the results of both conditions are pooled. Under condition L participated 20 randomly selected subjects from which we had to exclude the results of two subjects, who showed simulator sickness problems; 14 randomly selected subjects participated under both conditions D and N.

We found a bias for the $PSE = 1.0940$ from the psychometric function under condition D (76.88° GFOV). Detection thresholds of 75% were reached at gains of $g_{R[pitch]} = 0.8702$ for "smaller" responses and at $g_{R[pitch]} = 1.3378$ for "larger" responses. Gains applied within this range cannot be reliably estimated, i. e., subjects had problems to discriminate between a 40° real rotation and virtual rotations ranging between 34.8° and 53.5°.

For condition N, in which the head rotation gains for the most natural GFOV (88.34°) were tested, we determined a bias for the $PSE = 1.0510$ from the psychometric function. Detection thresholds of 75% were reached at gains of $g_{R[pitch]} = 0.8216$ for "smaller" responses and at $g_{R[pitch]} = 1.3004$ for "larger" responses. Subjects had problems to discriminate between a 40° real rotation from virtual rotations ranging between 32.9° and 52.0°.

For condition L (98.62° GFOV) we found a bias from the psychometric function for the $PSE = 1.1216$. Detection thresholds of 75% were reached at gains of $g_{R[pitch]} = 0.8265$ for "smaller" responses and at $g_{R[pitch]} = 1.4366$ for "larger" responses. Subjects had problems to discriminate between a 40° real rotation and virtual rotations ranging between 33.1° and 57.5°.

4.2.3 Discussion of E1

As mentioned above, we found a (positive) bias for the PSE in all considered conditions, showing that subjects tend to underestimate virtual pitch rotations. Subjects judge a virtual pitch as identical to the corresponding real rotation if the virtual pitch rotation is increased by 9.4% for condition D, 5.1% for condition N, and 12.2% for condition L. This result is consistent with [Jaekl et al. 2002]. With their experimental design and setup, they found 38% up-scaled virtual pitch rotations as most perceptually stable.

In our results, the detection thresholds are arranged almost symmetrically around the shifted PSEs. Hence, the amount of augmentation that can be applied to real-world pitch rotations without users noticing is larger than for attenuations, i. e., +33.8% or −13.0% for condition D, +30.0% or −17.8% for condition N, and +43.7% or −17.4% for condition L. This significant difference between unnoticeably up- and down-scaled pitch rotations may be caused by the momentum of the subject's head. Due to the HMD's weight, the proprioceptive feedback resulting from a new head orientation may deviate from the estimated feedback resulting from the prediction of the efferent copy signals. Forward estimation of the efferent copy signals produced by a motor command for a head rotation would predict more posture stability than received as feedback, because of the unfamiliar situation with the additional weight of the HMD. Hence, a virtual rotation that is mapped one-to-one to a corresponding real rotation may be underestimated.

4.3 Experiment 2 (E2): Discrimination between Virtual and Physical Roll Rotations

In this experiment subjects discriminated physical and virtual roll rotations (see Figure 2(b)). Subjects' task was to perform physical roll rotations with the HMD, while we applied different rotation gains $g_{R[roll]}$ to the corresponding virtual rotations under the aforementioned three conditions D, N, and L (cf. Section 4.1).

4.3.1 Material and Methods for E2

In this experiment we used the same experimental procedure as described in Section 4.2.1, i. e., we started trials with an adjustment screen that ensured identical start orientations for all trials at physical head pitch and roll angles of 0° with a tolerance of ±2°. After assuming the start orientation, subjects confirmed the task to either tilt the head right or left with a button press on the Wii controller, which caused the virtual scene to be presented on the HMD. When the subject performed a roll rotation of 40°, we displayed the written instruction to judge the discrepancy between real and virtual rotation in a 2AFC task. Subjects had to judge whether the virtual rotation was larger (up button) or smaller (down button) than the real rotation using the Wii controller.

In randomized order, we simulated different gains ranging between $g_{R[roll]} = 0.6$ (24° virtual rotation) and $g_{R[roll]} = 1.4$ (56° virtual

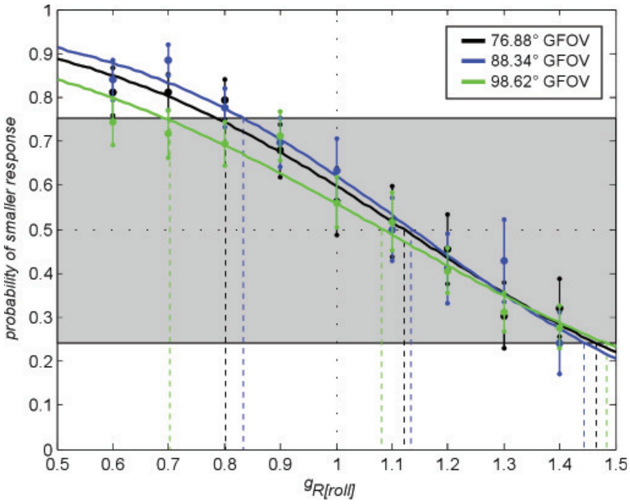


Figure 4: *Pooled results of the discrimination between virtual and physical roll rotation under (black) condition D ($g_{F[y]} = 1.0$), (blue) condition N ($g_{F[y]} = 1.1848$), and (green) condition L ($g_{F[y]} = 1.3649$). The x-axis shows the applied rotation gain $g_{R[roll]}$, the y-axis shows the probability of estimating a virtual rotation as "smaller" than the physical counterpart.*

rotation) in steps of 0.1. Each gain was tested 8 times in randomized order leading to 72 trials. As in Experiment E1, we tested these gains for the three conditions D, N, and L (cf. Section 4.1) in randomized order, resulting in 216 trials in total. We randomly chose the rotation direction between left and right for each trial. Both the position and heading direction in the VE were randomized and changed for each trial. Before the actual trials started, subjects performed 10 supervised training trials with alternating gains $g_{R[roll]} = 0.5$ (20° virtual rotation) and $g_{R[roll]} = 1.8$ (72° virtual rotation), which were excluded from the results.

4.3.2 Results of E2

Figure 4 shows the mean response over all subjects of the discrimination experiment in the three conditions. The black function shows the results for condition D ($g_{F[y]} = 1.0$), the blue function for condition N ($g_{F[y]} = 1.1848$), and the green function for condition L ($g_{F[y]} = 1.3649$). The x-axis shows the applied rotation gain $g_{R[roll]}$, the y-axis shows the probability that subjects estimated the virtual rotation as "smaller" than the physical rotation. The solid line shows the fitted psychometric function of the form $f(x) = \frac{1}{1+e^{a \cdot x+b}}$, with $a, b \in \mathbb{R}$. We found no difference between left and right roll rotations and pooled the data from the conditions. Under condition L participated 20 randomly selected subjects from which we had to exclude the results of two subjects, who showed simulator sickness problems; 14 randomly selected subjects participated under both conditions D and N.

We found a bias for the $PSE = 1.1205$ from the psychometric function in the native GFOV (76.88°) condition. Detection thresholds of 75% were reached at gains of $g_{R[roll]} = 0.8000$ for "smaller" responses and at $g_{R[roll]} = 1.4610$ for "larger" responses. Rotation gains applied within this range cannot be reliably estimated, i. e., subjects had problems to discriminate between a 40° real rotation and virtual rotations ranging between 32.0° and 58.4°.

For the condition with the most natural GFOV (88.34°), we determined a bias for the $PSE = 1.1351$ from the psychometric function. Detection thresholds of 75% were reached at gains of $g_{R[roll]} = 0.8474$ for "smaller" responses and at $g_{R[roll]} = 1.4429$ for "larger" responses. Subjects had problems to discriminate between a 40° real rotation and virtual rotations ranging between 33.9° and 57.7°.

A bias for the $PSE = 1.0823$ from the psychometric function was found for the significantly augmented GFOV (98.62°) condition. Detection thresholds of 75% were reached at gains of $g_{R[roll]} = 0.7078$ for "smaller" responses and at $g_{R[roll]} = 1.4769$ for "larger" responses. Subjects had problems to discriminate between a 40° real rotation and virtual rotations ranging between 28.3° and 59.1°.

4.3.3 Discussion of E2

We found a (positive) bias for the PSE for all considered conditions, showing that subjects tend to underestimate virtual roll rotations. Subjects judge a virtual roll as identical to the corresponding real rotation if the virtual roll rotation is augmented by 12.1% for condition D, 13.5% for condition N, and 8.2% for condition L. Consistently, [Jaekl et al. 2002] also found that perceptual stability is reached for up-scaled virtual roll rotations. They found 17% up-scaled virtual roll rotations as most perceptually stable. The discrepancy in the amount of required augmentation may be due to the different experimental design and setup.

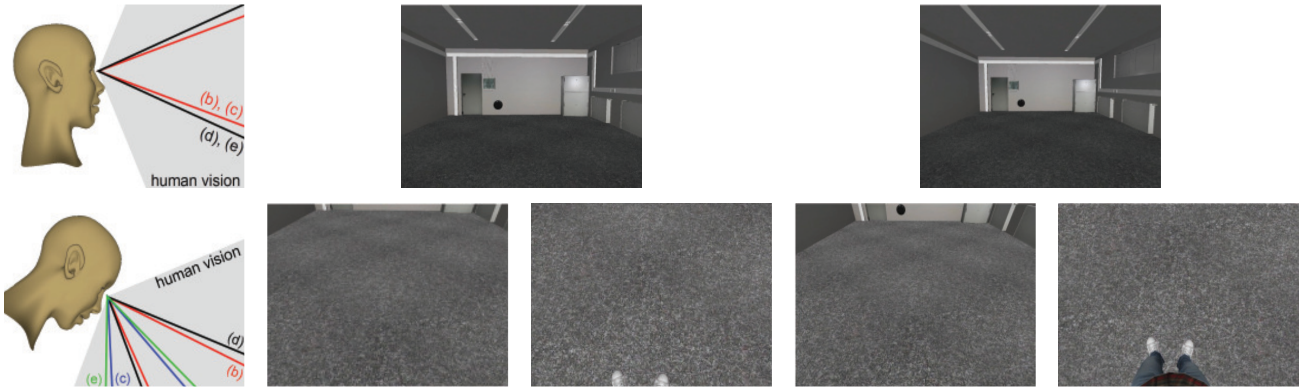
Similar to 4.2.2, in our experiment detection thresholds are arranged almost symmetrically around the shifted PSEs. Hence, the amount of augmentation that can be applied to real-world roll rotations without users noticing is larger than for attenuations, i. e., +46.1% or −20.0% for condition D, +44.3% or −15.3% for condition N, and +47.7% or −29.2% for condition L. This significant difference between unnoticeably up- and down-scaled roll rotations may be caused by the same arguments as explained in Section 4.2.3.

5 General Discussion

The results of experiments E1 and E2 show that for all tested GFOVs head pitch and roll rotations can be amplified significantly without users noticing the manipulation. In particular, under all conditions subjects estimated slightly up-scaled virtual head rotations as matching their real-world head rotations, i. e., the virtual scene rotates slightly against their direction of motion, which is consistent with results found in [Jaekl et al. 2002]. Interestingly, recent works investigating yaw rotations found that subjects estimated slightly down-scaled virtual head rotations as matching corresponding real-world motions, for which the virtual scene rotates slightly with the direction of motion [Steinicke et al. 2010; Jerald et al. 2008]. The discrepancy between the results of pitch and roll on the one hand might be due to the additional weight of the HMD, resulting in changed motor behavior of the subjects when tilting their head forwards or sidewards. On the other hand, the additional weight has less impact on yaw rotations, where the weight of the HMD is perceived as constant during rotations around the center of gravity.

Reduction of Required Head Rotations

Amplifying virtual head rotations by the amounts subjects estimated as matching corresponding real-world rotations has the benefit of reducing the overall effort that is required to explore a VE by means of head rotations. Figure 5 illustrates the effort reduction showing virtual views rendered (b) without manipulations, (c) with amplified head rotations, (d) with augmented GFOV, and (e) with both augmented GFOV and amplified head rotations for a 0° real-world pitch in the top row and a 45° downward pitch in the



(a) Real-world pitch (b) $g_{F[y]}=1, g_{R[pitch]}=1$ (c) $g_{F[y]}=1, g_{R[pitch]}>1$ (d) $g_{F[y]}>1, g_{R[pitch]}=1$ (e) $g_{F[y]}>1, g_{R[pitch]}>1$

Figure 5: *Illustration of GFOV augmentation and amplification of pitch rotations. Top row shows VE views for (a) a real-world 0° pitch rendered using HMD's native FOV (center) and augmented GFOV (right). Bottom row shows VE views for (a) a real-world 45° downward pitch rendered using HMD's native FOV (b) without amplified head rotations, (c) with amplified head rotations, and using augmented GFOV (d) without amplified head rotations, (e) with amplified head rotations. Furthermore, (a) illustrates the FOV's of (b), (c), (d) and (e) in comparison to the human vision.*

bottom row. We define effort as the amount of head rotations required to explore specific regions of VEs. Let θ denote the angular orientation of the head pitch, where $\theta = 0^\circ$ refers to a horizontal view direction, $\theta = -90^\circ$ to a view down along the gravitation vector, and $\theta = +90^\circ$ to a view up along the inverse of the gravitation vector. For instance, when we focus on pitch rotations and consider the effort required to see the feet of a virtual body in a VE from a horizontal start orientation, the effort is reduced as follows: In the case the user wants to see the feet of a virtual body with a HMD that provides 60° vertical DFOV, the user has to pitch the head by -60° such that the bottom border of the view frustum reaches -90°. When a GFOV gain $g_{F[y]} = 1.5$ and a head rotation gain $g_{R[pitch]} = 1.5$ is applied, the user has to pitch her head by -30° in contrast to -60° without any manipulations, i. e., the effort is reduced by 50%.

In general, the angular pitch rotation in the real world required to explore from a horizontal start orientation the complete range of 360 degrees of a VE is given by

$$\frac{1}{g_{R[pitch]}}\left(360 - DFOV \cdot g_{F[y]}\right),$$

where *DFOV* is the display's vertical FOV.

For the field of view gains tested in the experiments, we have a vertical *DFOV* of 52.75°. Applying the found PSEs as pitch rotation gains $g_{R[pitch]}$ to explore an entire 360° vertical FOV leads to a required effort of 307.25° without any manipulation, 280.85° for condition D, 283.07° for condition N and 256.78° for condition L. That means the effort can be reduced by 8.6% for condition D, 7.9% for condition N, 16.4% for condition L compared to the situation without any manipulations. The effort can be further reduced by applying the upper detection thresholds for each condition, i. e., 229.67° required effort for condition D, 228.78° for condition N, 200.47° for condition L. Consequently, the effort reduction is 25.2% for condition D, 25.5% for condition N and 34.8% for condition L.

In case of head roll rotations, the extent to which the user has to roll her head highly depends on the user's specific task. Since the effort reduction of an increased GFOV relies on the amount of rotation, we have calculated the minimal effort reduction when no field of view gain is applied, i. e., $g_{F[y]} = 1$. An effort reduction of at least 10.8% for condition D, 11.9% for condition N and 7.6% for condition L is achieved by applying the PSEs for each condition. The effort can be further reduced by applying the upper detection thresholds for each condition leading to a reduction of 31.6% for condition D, 30.7% for condition N and 32.3% for condition L.

Virtual Body

In a verification session after the experiments, we tested all PSEs and upper DTs for head rotations for all three GFOVs while subjects explored the experimental VE described in Section 4.1. We further displayed a static virtual body at the subject's tracked position in this session (see Figure 5(e)). We found that most subjects frequently pitched their head down in order to see their virtual body, and the manipulation gains led to more comfort by reducing trunk and head flexions (cf. Figure 1). One of our subjects stated,

> *"It felt natural to see my avatar when only pitching my head instead of making a forward bow in order to see my feet."*

Some subjects mentioned after the experiment that though they were able to detect manipulated head motions in some cases, they still did not find those distracting, even for the greatest manipulations that were applied, i. e., $+41.7\%$ scaled virtual pitch and $+43.7\%$ scaled roll head rotations. One of our subjects stated in an informal debriefing session,

> *"I knew I was going to be manipulated, but although I was sure at some points, I never felt distracted."*

We believe that greater manipulations can be used for applications that engage subjects in tasks not focused on detecting manipulated motions to further reduce the effort for exploration of VEs.

Questionnaires

We found no significant influence of the subjects' questionnaire responses on the results. The subjects' mean estimation of their level of feeling present in the VE according to the SUS presence questionnaire averaged as 3.24 for the pitch experiment E1, and 2.95 for the roll experiment E2. Kennedy's SSQ showed an averaged pre-experiment score of 14.96 and a post-score of 22.98 for the pitch experiment E1, and 15.50 respectively 19.41 for the roll experiment E2. The subjects further estimated the difficulty of the tasks with 1.65 on average on a 5-point Likert-scale (0 corresponds to very easy, 4 corresponds to very difficult). On comparable Likert-scales subjects revealed marginal orientational cues due to ambient noise (0.91) and light sources (0.26) in the real world.

6 Conclusion and Future Work

In this paper we analyzed subjects' ability to judge head pitch and roll motions in a HMD environment with different geometric field of views. Our results show that subjects estimated rotational real and virtual motions as similar when the real motions were scaled between $+5.1\%$ and $+13.5\%$ depending on the rotation axis and GFOV in a typical HMD setup, showing evidence for a slight underestimation of virtual rotations. The results provide an interval for manipulations of virtual head rotations, which can be used to map the typically restricted range for comfortable head rotations with HMDs to a greater viewing range in the VE, or to map a larger range of head rotations in the real world to a smaller range in the VE, e. g., if greater precision is required for virtual aiming tasks. We found that pitch rotations can be scaled up to $+30.0\%$ and -17.8%, and roll rotations up to $+44.3\%$ and -15.3%, for example, when the most natural GFOV is applied. For visual search tasks we believe that the effort due to head motions can be significantly reduced by combining augmentation techniques by at least 25.2% (cf. Section 5).

In the future we will investigate in more depth how perception of virtual motions is affected by characteristics of HMDs and manipulation techniques. In particular, we will further investigate the interrelation between augmentation of GFOVs, amplification of head rotations and other manipulation approaches like redirected walking or reorientation techniques [Razzaque 2005; Peck et al. 2008] that have the potential to make interaction in immersive VEs more effective.

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